MANTLE TRANSITION ZONE STRUCTURE BENEATH HAINAN AND ADJACENT AREAS DERIVED FROM RECEIVER FUNCTION ANALYSIS

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Abstract We have determined the upper mantle 410 km discontinuity and 660 km discontinuity structure and transition zone thickness beneath Hainan and adjacent areas by using receiver function method. The data used in this study are teleseismic waveforms recorded by 88 seismic stations in Hainan, Guangdong and Guangxi Regional Seismic Network and National Seismic Network during August, 2007 to March, 2010. The results show that the structure of 410 km discontinuity is complex below this region, which is depressed to 447 km locally. The 660 km discontinuity is simple relatively, with the depth around 670 km. The transition zone is thinned anomalously by 25±5 km within an area approximately 200 km in diameter centered northeast of the Hainan island, consistent with an excess temperature of ∼180°C. The locally thinned transition zone implies that the Hainan plume originates from lower mantle.

Key words Hainan plume, Receiver function, Upper mantle 410 km and 660 km discontinuity, Transition zone thickness

1 INTRODUCTION

Hainan and its adjacent areas are located in the intersection of the Eurasian plate, Indo-Australian plate and Philippine Sea plate. Since the Cenozoic, 10 periods and 59 times of volcanic eruptions occurred in this area, forming more than 100 volcanoes with volcanic karst reaching 4000 km²[1]. Maruyama suggested that the mantle plume exists under the lithosphere of the southern South China Sea[2], The S velocity structure obtained by Lebedev et al.[3] using seismic tomography methods shows low-velocity anomalies existing under the Hainan volcano. The global model[4–5] reveals that mantle plume may exist in the vicinity of Hainan, and originates in the lower mantle. But the spatial extent of low-velocity anomalies is large in the global model, and the morphology is uncertain. The location and morphology of low-velocity anomalies under the Hainan volcanic area revealed by the high resolution tomography model of the Chinese continent and adjacent area is very different from the global model, in the former the low-velocity anomalies are concentrated in the vicinity of Hainan from 200 km to 900 km depth, and the spatial extent is smaller[6]. The regional tomography model obtained by Lei et al.[7] using the data of 9 regional seismic stations shows low velocity anomalies extending slantways from the surface down to the bottom of the model around 300 km depth. The results of tomography show that the scope and origin of the Hainan plume is a controversial problem because of the limitation of resolution and research depth.

The mantle transition zone is the region between upper mantle 410 km discontinuity and 660 km discontinuity (hereafter referred as ‘410’ and ‘660’), where the morphology of the two discontinuities is affected temperature variations, and the depths to 410 and 660 respectively are increased and decreased by the upward going high-temperature mantle plume, resulting in thinning of the mantle transition zone. Therefore, we can infer the scope and origin of the mantle plume by studying the morphology of upper mantle discontinuities and the variations of transition zone thickness. Some scholars have studied the Hawaiian, Iceland, and the South Pacific mantle plumes using receiver function methods[8–13]. The depths of upper mantle discontinuities[14] have been estimated and the mantle transition zone thickness[15] bellow the QIZ seismic station located at Hainan island was calculated by using receiver function methods. The results reveal the thinning of the mantle...
transition zone below the seismic station. However, only one seismic station was used in these studies, which lead to a great uncertainty of the results, and they do not allow to reveal the lateral variations of the transition zone thickness, neither determine the existence scope of the mantle plume. In this study, we attempted to indicate the structure of 410 and 660 and lateral variations of transition zone thickness using the teleseismic waveform data recorded by 88 broadband seismic stations located in Hainan and adjacent areas by applying receiver function methods, and discussed the existence scope and origin of the Hainan plume based on the results.

2 DATA AND METHOD

2.1 Data

This study used the data recorded by 88 broadband seismometers of Hainan, Guangdong and Guangxi seismic networks from August 2007 to March 2010 (Fig. 1). We select high quality data from 529 teleseismic events with epicentral distances between 30° to 90° and magnitudes greater than 5.5. Totally 75 events with clear P wave first motion and high signal to noise ratios were used for receiver function analysis (Fig. 2b).

Fig. 1 Distribution of seismic stations used in this study and piercing points

The small triangles represent seismic stations. The big triangle represents Hainan volcano. The dots denote piercing points at 410 km discontinuity. The two perpendicular lines are the locations of receiver function profiles shown in Fig. 4.

2.2 Data Processing

Teleseismic P-wave receiver function is the time series resulted by the deconvolution between the vertical component and the horizontal component of three-component teleseismic records, which avoids the influence of earthquake source and the propagation path, so that it is mainly related to the structure beneath the stations. The receiver function method obtains the depth of discontinuities using the time intervals between direct P waves and conversions (Ps) of P waves at seismic velocity discontinuities beneath the seismic station, which is an effective method for studying the structure of crust and upper mantle velocity discontinuities beneath the seismic stations[16].

In data processing, we use the waveform data between 80 s before the P wave first motion and 100 s after the first motion. Firstly we rotate the two horizontal components to the radial and tangential components, and then obtain receiver function by deconvolution of the vertical component to the radial component. A total of 3595 receiver functions was obtained by using the frequency domain deconvolution method with Gaussian filter.
We set the ratio of the amplitude of direct P wave in the receiver function and the deviation of the first 60 s data in the deconvolution results as the signal to noise ratio. In order to maximize the quality of the results and ensure the quantity of data, we removed the receiver functions with the signal to noise ratio smaller than 25 according experience. In total 1842 receiver functions were selected in accordance with the above rules. Receiver functions of the PGX station with signal to noise ratio greater than 25 are shown in examples in Fig. 3.

In order to enhance the converted wave signals, we stacked the selected receiver functions using the coplanar stacking method. To eliminate the influence of different epicentral distances on arrival times of converted waves, all the receiver functions were corrected to reference epicenter $67^\circ$. The side length of each square patch was set to be 200 km, the moving step of the patch was 66 km at horizontal orientation, and the spacing of the patches was 10km in vertical orientation. Then we calculated the location of piecing points of receiver function ray at different depths, and receiver functions having P to S conversions that pierce the same patch were stacked using the $n$th root ($n = 2$) stacking method$^{8,18}$. The converted waves of direct P waves at 410 and 660 in the receiver function were enhanced after the stacking.

We transformed the stacked receiver function from the time domain to the depth domain using the IASP91 model. In order to guarantee the reliability of results, only when the number of receiver functions at the patch of 400 km and 700 km was greater than 50, the depths of P410s and P660s were picked. Finally, the mantle transition zone thickness was determined by the calculation of the depth of 660 minus the depth of 410.
3 RESULTS AND INTERPRETATION

3.1 Structure of 410 and 660

After the above data processing, we obtained the structure and transition zone thickness of 410 and 660 below the study area. Fig. 4 is the stacked receiver function profile, in which (c) and (d) are migrated stacking profiles corresponding to the time profiles (a) and (b) (profile location is shown in Fig. 1). The depth of 410 and 660 could be picked up along the maximum value of positive waves. The 1s change of difference between P410s and P660s in the time domain profile is equivalent to about 10 km variation of transition zone thickness. In the depth profile AA’ (Fig. 4c), 410 is undulating, the depth of 410 is 415 km at the western end, and sinking substantially to 447 km along the profile at 111.3°E, uplift to 417 km at 114.6°E, then depresses again to 432 km at 117.2°E, the eastern end of profile. There is a local stratification of 410 at the transitional region of depth variation; this may be caused by the sampling of depressed and normal 410 in the same stacking patch. The 660 is flat relatively around the depth of 670 km. In the depth profile BB’ (Fig. 4d), the depth of the 410 changes gradually from 422 km at 17.8°N to 440 km at 22°N, and uplifts to 426 km at 22.6°N, then extends to 24.1°N. The depth of 660 changes gradually from 679 km at 17.8°N to 671 km at 22.6°N, and depresses to 678 km between 23.2°N to 24.1°N. In general, the depth of 410 changes intensively under the study area with local sharp depression, while 660 is simple and flat relatively. In profile BB’, 410 and 660 are of anti-correlation between 20.2°N to 22.6°N, the sinking of 410 corresponds to the rising of 660, but the sinking amplitude of 410 is greater than that of relative rising of 660. In order to see the depth variation of the two discontinuities under the study area more clearly, Fig. 5 shows the depth distributions of 410 and 660. It displays generally sinking of 410 under the study area relative to the global average depth, 410 depresses substantially at northeast of the Hainan island, down to 447 km. The undulating of 660 is relatively small and 660 exhibits widespread slight sinking, which may be related to the existence of low velocity anomalies in the upper mantle. In this study, we
deployed time-depth conversion using the IASP91 model, and the calculation results show that the 2% even velocity anomalies above the 410 km could cause 10 km apparent depth variations of 410 and 660. The tomography model of China and its adjacent regions show that the upper mantle velocity anomalies of Hainan and its adjacent areas are less than 2%[6], therefore the influence of velocity structure above 410 km on the depths of 410 and 660 is less than 10 km.

3.2 Thickness of Transition Zone

The depth and structure of 410 and 660 are susceptible to the velocity model used in the calculation. Due to the propagation path of P410s and P660s above 410 km is largely the same, therefore differential arrival times of P410s and P660s are not affected by the velocity model above 410 km, only related to the thickness and velocity distribution of the transition zone. Temperature variation can also affect the thickness and velocity
of the transition zone, but the influence caused velocity change on differential arriving times is almost the same as the picking error. However, the influence of transition zone thickness change on differential arrival times is much larger. Therefore, the transition zone thickness determined by differential arrival times could obtain the temperature variation of the transition zone\[^{[19]}\]. Fig. 6 shows the transition zone thickness distribution of the study area, exhibiting obvious lateral changes of transition zone thickness. The average value of transition zone thickness of the study area is 244 km, an anomalous thin transition zone thickness area with the diameter about 200 km is present at northeast of the Hainan island, (thickness of 225±5 km), which is 25±5 km less than the global transition zone thickness average value, while the surrounding transition zone’s thickness is close to the global average. The location of anomalous thin transition zone thickness area obtained in this study is roughly consistent with the location of low velocity anomalies of the Hainan area at depth between 470 km to 660 km in the Lebedev tomography model\[^{[3]}\], but the area of anomalous thin transition zone thickness obtained in this paper is smaller than the low velocity area in the Lebedev tomography model.

4 DISCUSSION

4.1 Thermal Anomalies of the Transition Zone

It is accepted that the 410 is formed by the transformation from \(\alpha\)-olivine to \(\beta\)-spinel, and 660 is formed by the transformation from \(\gamma\)-spinel to perovskite plus magnesiowustite. The mineralogy experimental results show that the Clapeyron slope of 410 transformation is positive\[^{[20]}\], and the Clapeyron slope of 660 transformation is negative, so the increasing temperature can results in the decreasing of 410, uplifting of 660 and thinning of transition zone thickness. The 10 km change of transition zone thickness is equivalent to 70 temperature variation, the mantle transition zone is thinned anomalously by 25±5 km, which is consistent with an excess temperature of \(\sim180^\circ C\) in the transition zone. We suggest that the thinning of the mantle transition zone centered northeast of the Hainan island implies a high temperature Hainan mantle plume existing in the transition zone beneath the region.

Studies reveal that mantle transition zone thickness below some major hotspots shows obvious thinning, the mantle transition zone below Galapagos islands is thinned about 25 km\[^{[12]}\], which is equivalent to the abnormal thinning value in this study. The mantle transition zone below Iceland\[^{[8]}\] and Hawaiian\[^{[10]}\] hotspots is thinned about 20 km and 40 km, corresponding to 150°C and 300°C temperature anomalies in the transition zone, respectively. The thermal anomaly value of the transition zone located in northeast of Hainan island is between the thermal anomaly values of the transition zone below Iceland and Hawaiian.

4.2 Origin of the Hainan Mantle Plume

Courtillot divide the origin depth of hotspots into three categories\[^{[21]}\]: (1) Upper mantle, the origin of such hotspots may be associated with the convection of asthenosphere and the structure, stress and fracture of lithosphere\[^{[22]}\]. The results obtained in this study show that the origin depth of the Hainan plume is under 410. (2) The bottom of mantle transition zone. The super plume is upwelling to the bottom of the transition zone to promote small plume upwelling from the bottom of the mantle transition zone. (3) The bottom of lower mantle. The unstable convection of D’’ layer could cause the upwelling of plume\[^{[23]}\]. The numerical simulation and experimental studies show that if a mantle plume originates from the thermal boundary layer at bottom of the transition zone, the horizontal extent of high temperature anomalies in the thermal boundary layer would be much lager than the diameter of the plume\[^{[24]}\], and such high temperature anomalies will cause thinning of the transition zone in a wide range. The results of this study show that the transition zone is thinned anomalously within an area (approximately 200 km in diameter) in northeast of the Hainan island, but transition zone thickness around is basically normal, which means that the Hainan plume can not originate from the bottom of the transition zone. Therefore, the local thinning of the transition zone under northeast Hainan implies that the Hainan plume may originate from lower mantle. The 410 below the study area shows substantial sinking, corresponding to substantial the depressing area of 410 where the 660 uplift is smaller. This
phenomenon maybe due to the existence of low velocity anomalies in the transition zone and the low sensitivity
of 660 to temperature. This result is similar to the findings of Niu et al.\cite{9} about the south Pacific super plume.

Isotope and rock chemistry data suggest that the mantle materials of the Leizhou peninsula and northern
Hainan island have transitional characteristics of oceanic island basalts (OIB) and mid-ocean ridge basalts
(MORB), and are affected by the mixing of the ancient subduction zone material at the same time\cite{25}. The
formation of the Hainan plume maybe related with the subduction of the Pacific plate and Philippine Sea plate
from east to west, and the subduction of the Indian plate from west to east\cite{26}. Plate subduction to the bottom
of lower mantle will cause the upwelling of hot materials, which run through the transition zone, reaching the
surface, thus forming the hotspots\cite{27}.

5 CONCLUSIONS

In this study we obtained the structure of 410 and 660, and transition zone thickness beneath Hainan and
adjacent areas by the receiver function method, using teleseismic data recorded by 88 broadband seismometers
of Hainan, Guangdong and Guangxi Seismic Networks. The results show that the 410 depresses locally, to 447
km at maximum, while the 660 is relatively flat. The transition zone is thinned anomalously by 25±5 km within
an area approximately 200 km in diameter centered northeast of the Hainan island, consistent with an excess
temperature of ~180°C. The recent tomography and geochemical studies suggest that a mantle plume exists
around the South China Sea. The results of this study provides new seismological evidence to this inference,
and defined the existence scope of this plume to a better degree. The locally thinned transition zone revealed
by this study implies that the Hainan plume may originate from lower mantle.

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